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HOLOGRAPHIC MICROSCOPY FOR THE DETERMINATION OF FAILURE MECHANISMS IN MONOLITHIC CIRCUITS

by Raoul F. van Ligten

Prepared by
AMERICAN OPTICAL CORPORATION
Framingham Centre, Mass.
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Dr. James Cline
Technical Monitor
NAS 12-584
Electronics Research Center
575 Technology Square
Cambridge, Massachusetts 02130

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INTRODUCTION

Semiconductor Device Inspection and Testing

If one were to perform an operations research study on the "optimum strategy" for semiconductor device testing, the conclusion reached would probably agree with the "common sense" one of testing at all stages from design prototype to final system assembly until the incremental inspection cost is no longer balanced by the expected losses associated with a system failure. Considering then the generally low production costs of semiconductor devices, the much greater costs of heading and encapsulating, connecting and interconnection into a system, and finally the somewhat disasterous consequences of device failure in modern complex and unattended systems, inspection and testing is best applied at the earliest feasible stage.

Clearly then [if the pressures of the market place allow it] complete testing at the design and pre-production prototype stage is most beneficial for removal of failure-prone production or operating features of a design and thereafter, during the production and device assembly stages a considerable investment in quality control is justified.

This is of course hardly news to the device supplier, but as the art has developed from individually processed chips, to mass produced wafers to discrete devices, through integrated circuits, and now to MSI and LSI, testing techniques have had to change in the direction of more sophistication and expense to keep up with the demands of greater uniformity, reliability and longer lifetimes under extreme environmental conditions. Such testing has been a necessity in order to improve yields [and thus lower costs] in a highly competitive business, but beyond a certain point, complete testing to predict <u>future</u> failure becomes an impossibility.

Table I is a partial summary of the types of design and production defects that can occur and the tests that currently or potentially might be used to detect them.

The available testing and inspection techniques for semiconductor circuit prototyping and production are largely limited to static and dynamic electrical terminal tests; direct visual inspection of surfaces under microscopes; visual inspection of

TABLE I - SEMICONDUCTOR CIRCUIT TESTING

Testing for:	Technique used:	Difficulties
Prototype Stage		
Poor temperature distribution	IR Thermography	Resolution
	Liquid crystals	
Poor dimensional tolerances	Visual inspection	
Production Stage		
Bad photography dust, registration, focus	Visual inspection	Oversight
Improper Processing		
Diffusion: wrong depth concent.	Electrical tests	Test is much later
Etching: over, under	" , visual	"
Oxidation: over, under	"	"
Metalization: shadowing, broken leads	"	"
Surface contamination	"	"
Bad static electrical char.	Microprobing of input and output terminal for static characteristics	Static testing only
Assembly Stage		
Faults due to bad dicing	Visual inspection	Oversight
Improper header bonding	Visual inspection	Oversight
Connections to header: faulty bonds at header faulty bonds at chip lands	Visual inspection	Oversight
Encapsulation:		
Leaks	Leak test	
Surface contamination	Life tests	Time and cost
Environmental:		
Temperature	Life Test [Static Electrical]	Usually not run
Humidity	"	
Vibration and shock	"	
Faulty dynamic electrical characteristics	Automated electrical testers	

Usage
Lead failure under shipping, handling, assembly into system, and use; Catastrophic electrical failure [runaway, breakdown, etc.]

chip surfaces coated with heat sensitive liquid crystal; or visual inspection of infrared thermographs.

Of all these tests, the go-no go static electrical testing of device terminal characteristics is the simplest, cheapest, and most reliable method of weeding out "bad" units, at a very early stage. Similarly, automated and computer controlled dynamic electrical testing can further eliminate off-specification units prior to shipment. There is a limit, however, in how far such tests can go in the elimination of "good" devices which have a potential for either catastrophic failure [lead breakage, semiconductor failure] or degradation to unreliable dynamic operating conditions in a service environment.

Life testing over environmental extremes of temperature, humidity, shock, and vibration is currently quite expensive and may prove impossible for LSI circuits of moderate complexity in which the number of input-output combinations becomes exceedingly large.

Conventional visual testing is limited to upper surface conditions and indications and thus may not show up some inadequacies in bonding, metallizing, or passivation which, while leading to future service failures, are undetectable electrically. Defects below the surface obviously cannot be seen, and even for surface defects, there is a high probability for oversight from the shear tedium of constant visual searching.

Laser holography and infrared scanning techniques have a potential for locating internal defects that are manifest in abnormal temperature or strain characteristics. Such techniques however must be applied prior to encapsulation and will again most likely entail a visual inspection of an image to detect malformation.

Thus, while strong arguments can be raised for the value of complete device testing, the problem of <u>predictive</u> testing remains difficult.

Holographic Microscopy of Integrated Circuits

From the preceeding paragraphs it is evident that new methods must be developed to test integrated circuits throughout the various stages of design and production.

One of these methods that appears promising is that of Holographic Microscopy or the application of microscopy techniques to holographic manipulations of images of microcircuitry. In order to determine the usefulness of this method for testing integrated circuits, a basic understanding of the characteristics of Holographic Microscopy is necessary. The three following sections present relevant factors of microscopy, interferometry and a general discussion of Holographic Microscopy. Following these sections, a detailed discussion of the application of holography to testing integrated circuits is given along with results obtained.

The study performed under this contract has resulted in a useful technique to store information about IC's and a posteriori apply known microscopy techniques to the study of the IC's. In the prototype stage or study phase this is of significance. Particularly, holographic interferometry can be efficiently used in the several stages of metallization, shadowing, surface contamination and to inspect for over or under etching, all employing the sensitivity of interferometry around $\lambda/50$ in the wavefront (in reflection $\lambda/100$). When utmost care is given to the interpretation of the interference fringes, it is possible to obtain a sensitivity of $\lambda/200$ in reflected light.

To study diffusion effects it has been suggested that the local phase variation of the detail be measured by illuminating the wafer from the substrate side with infrared light to which silicon is transparent. Interferometry techniques will yield from the wavefront thus refracted, an optical path difference (OPD) which is proportional to the refractive index change multiplied by the diffusion depth. The refractive index in turn is related to the diffusion concentration.

The gold-aluminum bond at the pads on the chip where the gold leads are connected is suspected as problematical and worth inspecting. In future studies the resolution and interferometry facility of Holographic Microscopy should be considered to inspect these bonds.

Recent development in lensless Holographic Microscopy and speckle removal techniques have made it attractive to use holograms as the masters for printing the detail on the wafers. A suggestion is made in that direction.

SURVEY OF MICROSCOPY

To begin the detailed discussion of the use of holography as applied to microsystems, a brief survey of existing microscope techniques is presented below. This background should allow the reader to interpret the findings in this report with confidence.

The various types of microscopy can be listed according to the type of object to be observed. Two basic types of objects can be distinguished: (1) opaque objects and (2) phase objects. All other objects can be classified as some combination of these two. For example, when absorbing objects are used, they may be opaque for one wavelength and transparent for another. Furthermore the optical pathlength (OPL) can also be a function of wavelength.

Opaque Objects

At different wavelengths it is customary to observe opaque objects with brightfield illumination, darkfield illumination or vertical illumination.

When brightfield illumination is used, the background of the object under observation is brightly lit. The consequences of this are comprehensively described by F. Zernike.[8] The circumferences of the objects can be well distinguished and if the objects are not fully opaque, the absorption changes are visible.

Darkfield illumination is used to show only the edges clearly. There is a distinction between central darkfield and oblique darkfield which Zernike describes in the same article mentioned above. In general, darkfield methods are sensitive to absorption-gradients and phase-gradients. It gives the microscopist an extra clue about the object. When the object is completely opaque but has some reflectivity, then vertical illumination is applied. This illumination is incident on the object from the same direction that the observation is made. In this case surface texture and steps in the object can be observed.

For low magnifications, stereo microscopy is often used to show the contour of the object as well as the three dimensional shape. However, a very basic problem limits the three dimensional fidelity of such a observation, i.e., the lateral magnification of such a system is the square of the transverse magnification. A spherical object will appear as an ellipsoid. When the transverse magnification is high, the observation in depth in image space behind the microscope objective is limited because the combination of the eyepiece and the eye of the observer has a limited depth of field. Translated in object space, this gives a depth of field equal to that of the combination magnification of the objective. Typically, the eye with a 10x eyepiece has a depth of field of about 2.5 - 3.0 mm. When an objective of 43x is used, the depth of field in the object is about 1.5 - 2μm. Objects of a longitudinal extent larger than 1.5 - 2μm cannot be seen completely with a combination of a 43x objective and a 10x eyepiece.

A stereo microscope can be made according to two basic methods. In one method, the visual channels are provided by two separate and identical microscopes of relatively low magnification, side by side. The objectives have a small numerical aperture and low magnification. The second method uses one microscope with an objective of high numerical aperture. A prism system is placed between the objective and the two eyepieces to provide two images. The optical system is then adjusted so that the images of the eye pupils are placed side by side in the aperture of the objective. The high numerical aperture of the objective passes light through the microscope which contains information of the object as seen from a large range of aspects.

Phase Objects

Phase objects are made visible by transforming phase-information into amplitude information. The commonly used methods in microscopy of phase objects are darkfield illumination[8,10] oblique brightfield[8,10] defocusing,[8] normal interference,[10] small-shear interference contrast,[11] phase microscopy[8,9,10] and polarization microscopy.[10] Other techniques more typical for other areas of optical observation of phase-objects are knife edge, "wire obstruction" and other occluding methods.

Darkfield illumination, oblique brightfield, defocusing, and small-shear interferometry can be regarded as edge enhancement techniques. There is, however, a problem of image fidelity. Darkfield has been discussed before. Oblique brightfield will yield an image which shows the gradients in the object. The fidelity of such an image is quite good and can be regarded as an image showing shadows caused by a finite source which casts light rays on the object in one slanted direction. The contrast of the shadows, however, is rather low. This limits the minimum gradient in the object that can be observed. Defocusing techniques will show that something is present. The fidelity of the image is naturally poor and only the gross circumference of rather large objects will resemble the actual shape.

Normal interference microscopy is the application of two beam interferometry to microscopy. The object bundle is combined with a reference bundle of uniform phase and amplitude. When the phase variations in the image wavefront are not in excess of a half wavelength, the interference of the two wavefronts can yield an intensity variation which is nearly proportional to the phase variation. This is achieved by making the interference bundle propagate in the same direction as the object bundle and by putting the center of curvature of this reference bundle coincident with the source that appears to illuminate the image. When these two origins are not coincident, fringes are visible. In general, these fringes are contours which describe the phase variations in the image. In case of phase variations larger than a half wavelength, the coincident sources will yield interference fringes at multiples of positive and/or negative differences of a wavelength. An offset is often used to yield again the contours describing the phase-variations.

Small-shear interferometry as chiefly introduced by G. Nomarski,[11] is a method used to enhance the gradients in refractive index, or in general, optical path. The image looks the same as that obtained with oblique brightfield except that very good extinction can be obtained in the shadows. The smallest gradient that can be detected is limited only by the brightness of the image. Thus far, this method is the best in existence to translate a phase-image into a high fidelity amplitude image with resolution limited only by microscope objective and the wavelength of radiation.

Phase microscopy[8,9] is a standard technique used especially in the field of biology and medicine. It can translate a phase-variation into an amplitude variation, with proportionality between the two when the phase-variations in the object wavefront are smaller than a half wavelength.

Polarization microscopy is the type generally done on birefringent objects or microscopy done with birefringent components in the instrument.

The simplest form of polarization microscopy on birefringent objects is that whereby the object is viewed between crossed polarizers. Bright and dark regions will be shown in the image. In the case of crystals, inferences can be made about the symmetry groups. As a function direction in the crystal, measurements can be made on the difference in the slow and fast refractive indexes by introduction of birefringent compensators between the polarizer and analyzer. A Bertram-lens is often built into the microscope to allow the observation of the Fraunhofer diffraction pattern of the image.

With the advent of the laser, the question arose as to whether this new light source could offer a new field of microscopy that would yield information that could not be obtained with conventional methods. The answer to that question lies in the information present in a microscopic image obtained by laser illumination as compared to that obtained by illumination with conventional light sources. All other forms of imagery with a laser compared to imagery with conventional light sources should be included. It is immediately evident that accurate knowledge of the phase of the laser illumination should yield better phase information in the microscope image. It does not mean, however, that such information can be readily derived from a laser illuminated object. The spatial image quality should be comparable to that obtained with conventional sources. This is certainly not the case. Images obtained from incoherently illuminated objects can be regarded as a collection of incoherent spread functions, of which the energies have to be added according to the convolution theorem. Images obtained from coherently illuminated objects can be regarded as a collection of mutually coherent spread functions, of which the amplitudes have to be added. This leads to interference patterns between the different spatially disturbed spread functions, i.e., it gives rise to speckle patterns. For microscopic objects the speckles may have the same dimensions as the object detail so it is important that some form of destruction of the coherence must be present to obtain good image quality, yet there should be enough coherence left to take advantage of the long interference length of the laser source. In general, the laser will relieve instrumentation problems in two beam interference microscopy where the reference wavefront is obtained from a bundle that does not traverse the same path as the imaging bundle.

INTERFEROMETRY

In order to understand the principal methods used to detect changes in an integrated circuit while they are electrically activated, it is important to discuss interferometry separately. In the holographic microscopy system one or two of the many interferometric methods are used to detect such changes.

Interferometry refers to the process whereby light waves interact with each other in such a manner that the wave properties contribute to the final result. For instance, the relative phase of the light waves will sometimes cause enhancement or attenuation of the total amplitude. It is necessary that the waves have the same wavelength and be sufficiently coherent to permit interaction. The term "coherent" can be explained as sufficient organization in the interacting waves that at the point in space where they meet, each wave "knows from the other how it is vibrating." This can be achieved by deriving the waves from the same point in a light source and leading them to the point where they should interact. In practice however, a point source does not produce enough energy to enable observation of the light waves. Therefore, usually a small, but extended area of such a light source is used to do interference experiments. The consequences of using more than one point in the source gives rise to less organization between interfering waves. Each point in the extended source fires independently from the others and thus causes in general a lack of organization at the region of interference. (Only when the paths over which the several waves are led to finally interact with each other, are equal in length will there be organization.) The result of this interference is an addition of effects, each of which is a result of interferences taking place between waves emanating from the same point in the light source. Thus it can be seen, that when the points in the light source are many and widely separated, all the interference effects will average out to a mean value.

When the waves departing from one source point propagate in space and while doing so expand in the forward half space, the three dimensional distribution, with the characteristic that the optical path measured from the same point of departure in the source be the same, is called a wavefront, or an equiphase front. When one such wavefront is led over two separate paths and subsequently recombined interference will occur between the wavefronts. A pattern of dark and bright fringes appears at places where the path difference between the two wavefronts is $(\lambda/2 \pm k\lambda)$, where λ is the wavelength and k is an integer. The bright fringes occur where the path difference is $(\lambda \pm k\lambda)$. If now, many more adjacent source points are used to generate wavefronts and they are led over the same two separate paths, the fringe pattern which will be produced consists of an energy addition of all the patterns that were formed by each individual adjacent point in the source. It can be seen that if the apparent source size is as small as seen from a position on the wavefront, all the light paths leading to that position are equal in length. Therefore, the appearance of the fringe pattern does not change very much when the source is extended. The changes will occur when the apparent source size is such that path differences between rays originating within the small extended source and leading to the same position on the combined wavefronts take values on the order of $\lambda/2$.

Two-Beam Interferometry

The phenomenon described above can be used in many arrangements leading to different uses. The simplest class of interferometry is done with two beams and accordingly called two-beam interferometry. For the purpose of this work only this category will be discussed in more detail. Although the source choice can be any, for the purpose of both practice and simplicity, a point light source is chosen. When a laser is used, this selection is very good because for all practical purposes a laser beam brought to focus at the focal point of a lens is as good as a point light source with a high intensity. It means that little care need be taken in the choice of the path difference between the two beams in order to achieve interference.

The Michelson two beam interferometer. - This method is typified by the instrument of Fig. 1. The light from a laser is focused to become a point light source at the focal point of a well corrected collimator lens, to form a plane wavefront. This wavefront is split in two by a beamsplitter and led over separate paths, each containing a plane mirror. The two wavefronts are subsequently reflected back and recombined at the beamsplitter. From there, the two wavefronts travel common paths in the direction of the observer. If all the light is focused through the pupil of the observer, the complete wavefront can be observed. By angular adjustment of the mirrors the angle

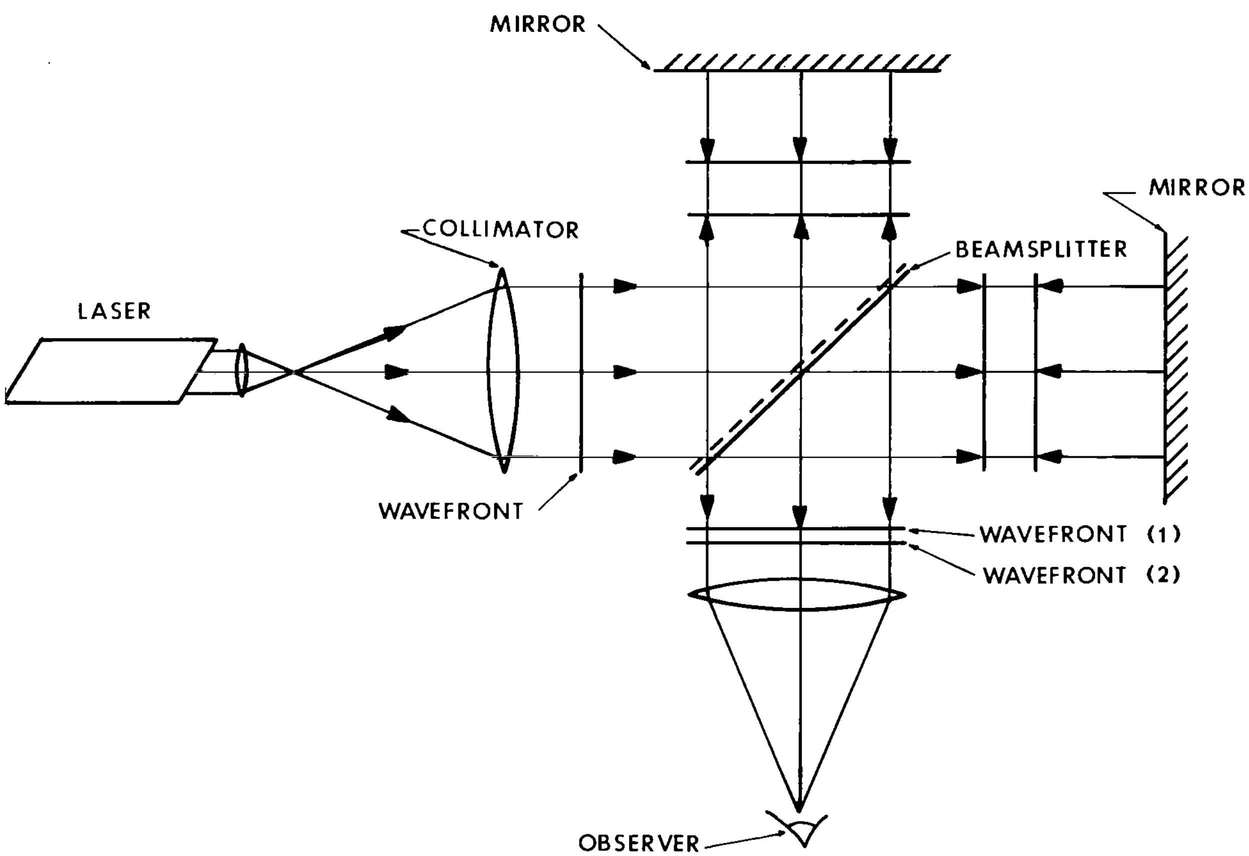


Figure 1. Michelson two-beam interferometer

between the returning wavefronts can be chosen. By linear adjustment of the mirrors in the direction of propagation of the light, the phase retardation of these wavefronts can be regulated. If the two plane wavefronts are inclined relative to each other, the familiar straight wavefront fringes will appear. The larger the angle between the two wavefronts, the finer the fringes.

In operation, a transparent object is placed in one of the arms of the interferometer. It will, in general, alter the wavefront. When, on the return trip after second passage of the beamsplitter, this modified wavefront interferes with the unaltered wavefront, a fringe pattern will be formed. This two dimensional pattern departs from the straight fringes. As a function of the place in the two dimensional plane, the departures from the straight line pattern represent, exactly, the phase variations in the unknown object. Since in the interference of the two plane wavefronts, the step from one fringe to the other was brought about by a phase change of $\lambda/2$, this pattern provides, under the given angular portion of the mirrors, a calibration. (See Fig. 2A). When the unknown object is placed in one of the arms and the interference pattern is altered into one as shown in Fig. 2B the following interpretation can be made. In a strip, d cm wide, the interference lines are displaced by 2/3 the original fringe width. This corresponds to a phase change of $2/3 \times \lambda/2 = \lambda/3$. The placement of a transparent material in one of the arms necessarily requires the light to pass twice through such a medium. The actual phase difference in the material is, therefore $1/2 \times \lambda/3 = \lambda/6$.

It can be said that the fringe shape is directly proportional to the phase variation contours in the object. If the two plane wavefronts were not mutually inclined at the outset, a uniform intensity would have appeared on the exit lens of the interferometer.

This type of interferometry is often referred to as Normal Interferometry. It is the two-beam interferometry whereby the perturbed wavefront is compared with a uniphase wavefront, in particular, a plane wavefront or a spherical wavefront. The reference wavefront and the unknown wavefront can be either mutually inclined or not.

In Holography this method can be successfully applied. A hologram is first made of a plane mirror on the microscope stage in the place of an integrated circuit (IC) in Fig. 3.

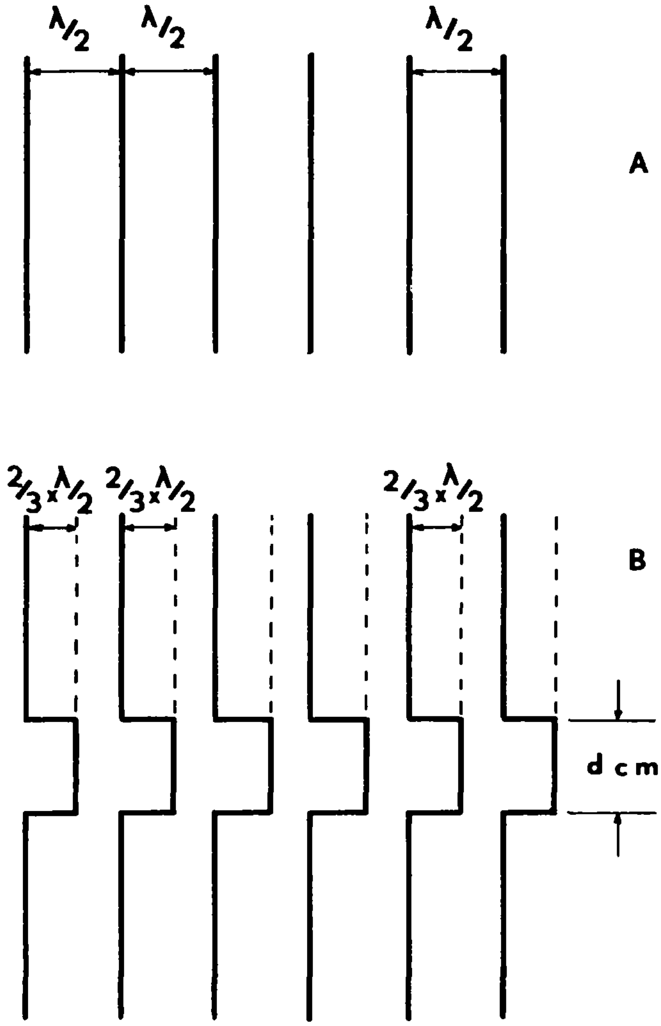


Figure 2. Interference patterns in Michelson interferometer.
(a) Interference between two plane wavefronts
(b) Interference between plane reference wavefront and a wavefront where a strip of width d cm has a phase step of $2/3 \times \lambda/2$.

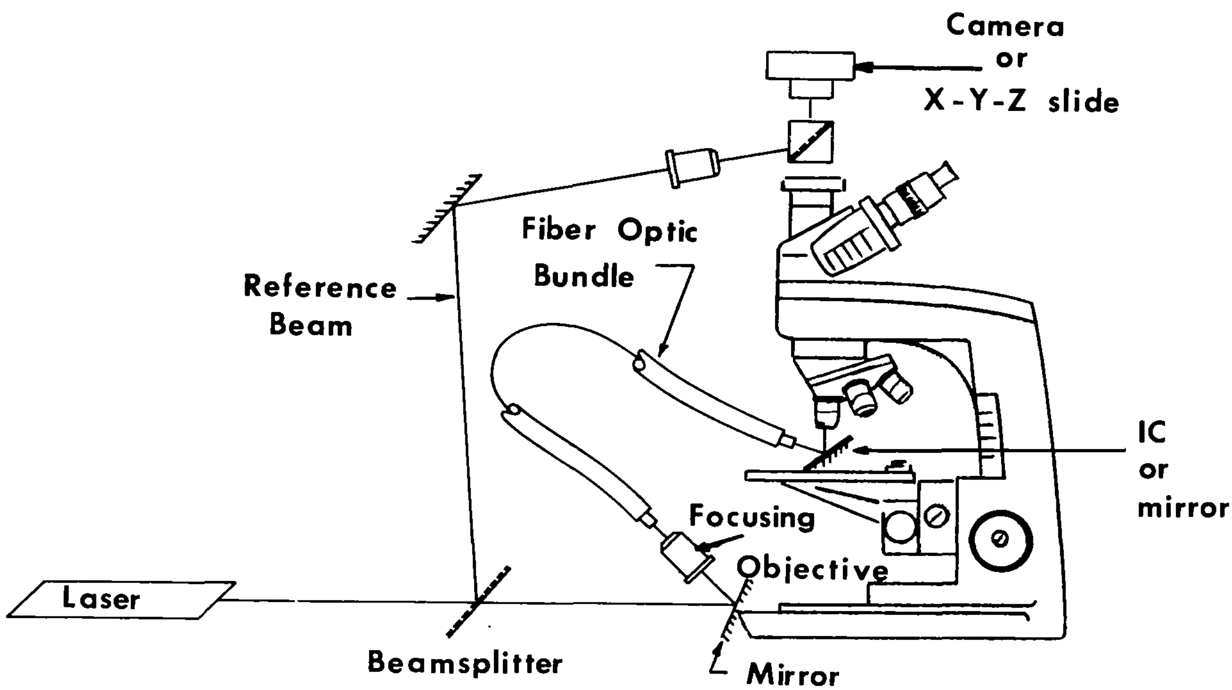


Figure 3. Front illumination modification in Holographic Microscope.

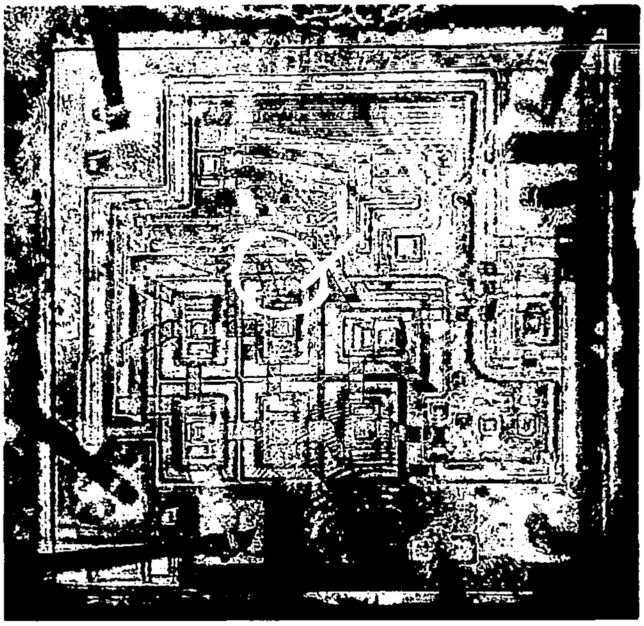
After development of this hologram, it is placed back in the position where it was taken. The reference beam in Fig. 3 now reconstructs the wavefront that came from the flat mirror. But, the wavefront from the flat mirror on the microscope-stage is still passing through the microscope. Thus, two wavefronts are present, both representative of the plane mirror. This is comparable to the case of Normal Interferometry with two uniphase wavefronts. When now the mirror is replaced by an IC, the bundle transmitted through the microscope is no longer representative of a plane mirror, but so modified that it represents the phase departures on the IC. The reconstructed wavefront is still representative of the original plane mirror. Thus, Normal Interference is obtained between a uniphase wavefront and a modified wavefront. The actual image obtained can be seen in Fig. 4(a). By inclining the wavefronts relative to each other a pattern is obtained as shown in Fig. 4(c). Fig. 4(b) and (d) are similar to Fig. 4(a) and (c) respectively except that now the IC's were activated.

If there was a way to now make a fringe pattern that represents only the difference between Fig. 4(b) and (a) or between Fig. 4(d) and (c), an immediate result could be obtained about the difference between the activated and unactivated IC. Such a pattern or map can be derived from the fringe patterns of Fig. 4, but this procedure is very time consuming.

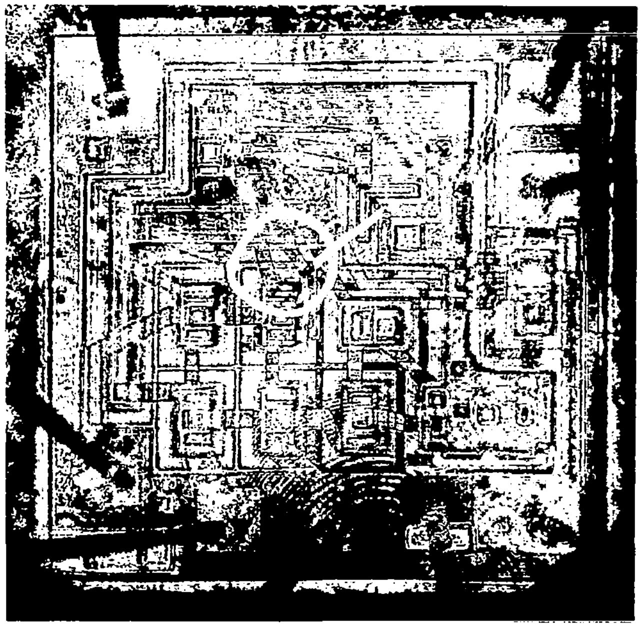
In the following a method will be described known as Differential Interferometry, which will yield just such a difference in patterns.

Differential Interferometry

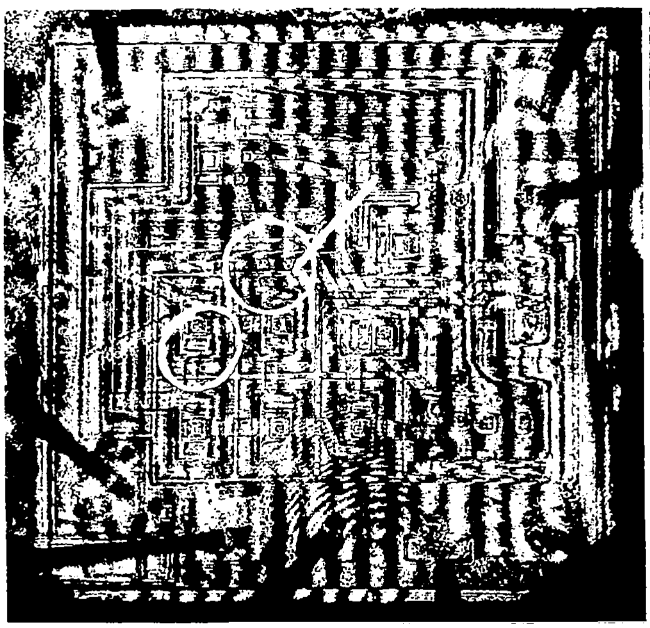
In order to detect only differences in phase variations it is necessary to also modify the reference beam or better, the comparison beam. The latter consists of a uniform phase in normal interferometry. The uniformity must be so modified that at the places where the object wavefront departs from the constant phase, it is changed by an amount equal to that departure. When this procedure is followed for all the points on the comparison wavefront, the latter is modified into the same wavefront as the object wavefront. A separate class of two-beam interferometry has been introduced where the object-modified wavefront is split in two identical wavefronts that are recombined. When the recombination is achieved by exactly superimposing one onto the other such that the corresponding points overlap,



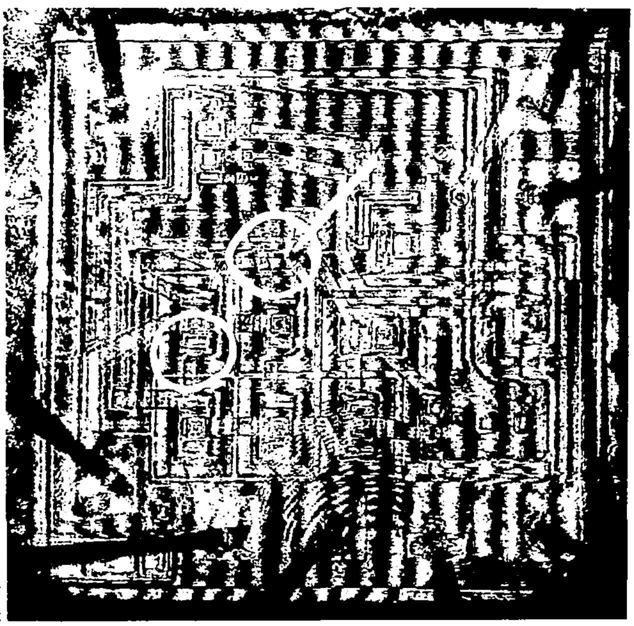
(a) normal reference beam, unactivated IC



(b) normal reference beam, activated IC



(c) tilted reference beam, unactivated IC



(d) tilted reference beam, activated IC

Figure 4. Normal Two-Beam Interferometry

there should be one uniform fringe over the exit pupil of the interferometer. This sometimes cannot occur when the detail in the object is such that abrupt phase changes take place. This causes diffraction fringes which are difficult to match and consequently will not disappear.

In Fig. 5, the situation is shown whereby the two identical wavefronts are sheared in the plane of the object. Now a compound phenomenon can be observed which generally is an image. This image can be very useful when the shear performed in the image plane is small. From Fig. 5 it can be seen that an intensity departing from uniformity only occurs where the slopes in the wavefronts are not tangent to the shear direction. For a sufficiently small shear it can be shown that the intensity variation in the image is proportional to the first derivative of the wavefront contour in the direction of the shear. A typical example is shown in Fig. 12 of a sample of fresh red blood cells. In Fig. 12(b) two wavefronts derived from the object were sheared in the object plane and observed. It appears as if a light source was aimed from the upper right hand corner at the blood cells illuminating them under near grazing incidence. It can be seen that the cells are discs with an identation in the center.

With a further application of holography, a new type of interferometry can be identified: Holographic Differential Interferometry. Two types can be described. One is space differential interferometry as shown above and not typical for holography and the other is time differential interferometry which can only be practically achieved through use of holographic methods.

Holographic Differential Interferometry

In this process the two beams are obtained not by an interferometer but by a hologram made from the object wavefront and by the object wavefront itself. The hologram is first made of the object (not of a substitute mirror as in Holographic Normal Interferometry) and subsequently repositioned in place where it was taken. The hologram reference beam functions as the reconstruction beam and reconstructs the object wavefront as if it was coming from the object. Concurrently, the object is illuminated in the holographic arrangement, and provides the second wavefront, identical with the reconstructed wavefront.

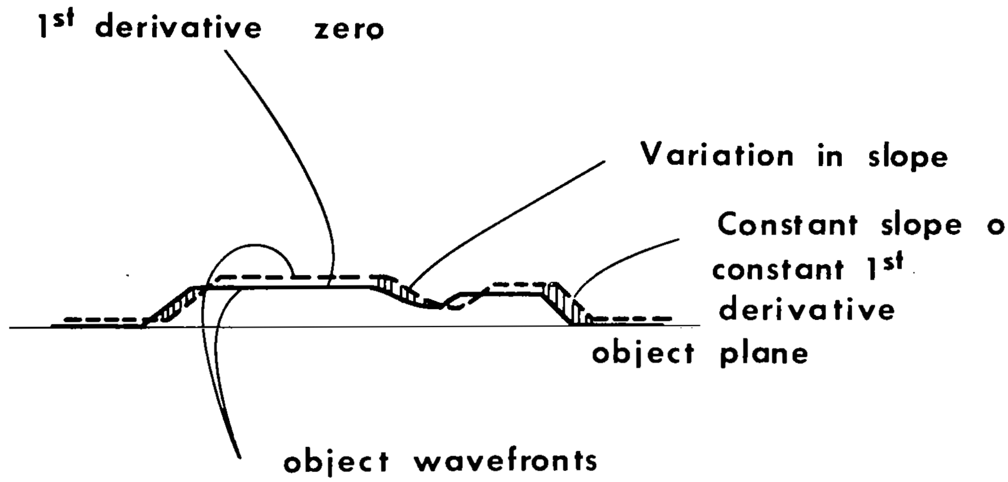


Figure 5. Linear shear in object plane.

From here on the wavefront obtained from the hologram is the comparison wavefront. When nothing is changed in the object between the time of taking it's hologram and the present, the same situation exists as in conventional differential interferometry. This is called Space Differential Holographic Interferometry.

Now keeping in mind that the comparison wavefront is still unchanged, the object wavefront can be one that will change as time progresses, either by time dependent physical property changes of the object or by inducing changes through some external means. This change becomes apparent in the compound image and cannot be compared with any image obtained in conventional interferometry. There the comparison wavefront will change as the object wavefront changes. Moreover, the change is exactly the same as that in the other wavefront. Clearly, for time variant phenomena, holographic interferometry yields uniquely useful results. This category of interferometry is called Time Differential Holographic Interferometry or Time Sequential Interferometry. This technique was applied to the study of integrated circuits. The contention is that upon activation of an IC, the different thin films deposited on the chip may act sufficiently different thermally to cause local expansions in the material. If these expansions are excessive it may indicate a failure mechanism which cannot be detected by usual optical observation. Fig. 6(a) and (c) show the differential interferometry pattern obtained for the unactivated IC. Note that in Fig. 6(a) the same appearance is prevalent in the blood cells in Fig. 12. The equivalent grazing incidence source appears to come from the righthand side. In Fig. 6(b) a small tilt was introduced between the two wavefronts. The result is obviously the presence of straight interference fringes superimposed on the image (a). In the right hand column the images are shown after the IC was activated. Fig. 6(b) shows that the protrusions in the detail, as could also be seen in (a), have substantially "grown." This growing effect is a time differential event. The appearance of the protrusions is a space differential phenomenon. In Figure 6(d) the illustration is even more dramatic. The relatively straight fringes of Fig. 6(c) have substantially taken a saw-tooth appearance. The grown protrusions are even clearer here. What the extent is of normal expansion is unknown and should be empirically established.

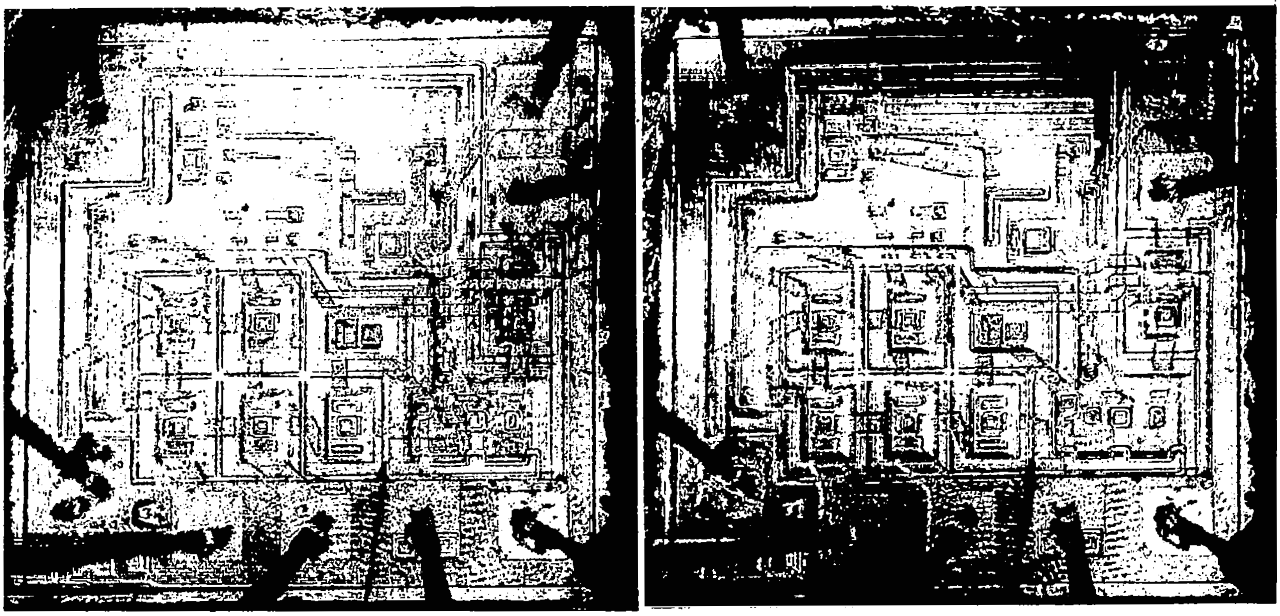
In resume it can be said that holography has offered an entirely new form of interferometry, which is unique in its kind: Time Differential Interferometry. The pioneers in this field are R. L. Powell and K. Stetson[12] as well as L. O. Heflinger et al.[13] Due to the work of R. F. van Ligten,[14] this interferometry can be applied to microscopic objects. The first substantial experimental results for Time Differential Interferometry were obtained with the integrated circuit as shown in Fig. 6.

HOLOGRAPHIC MICROSCOPY

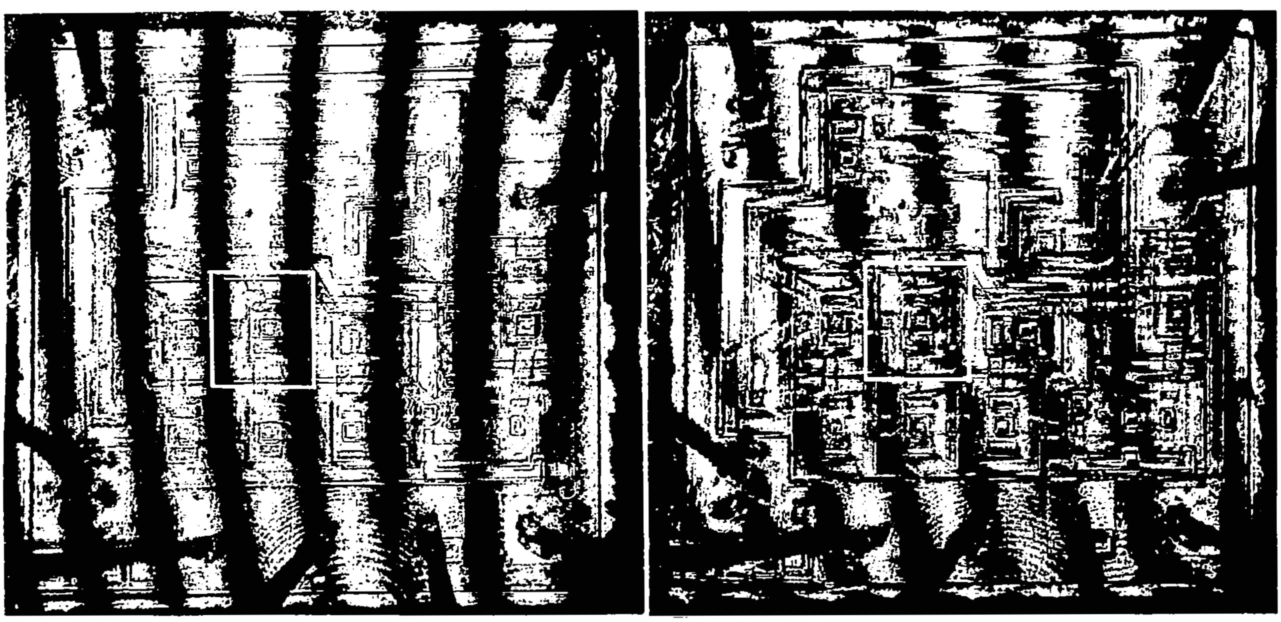
Holography is a very significant and non-obvious application of the laser. When applied to microscopy many possibilities present themselves. The first significant property is that a record can be made of the object in amplitude and phase, which can be later investigated with all the methods mentioned above. When, in microscopy, a phenomenon has to be studied which changes with time, holographic microscopy definitely offers numerous advantages over direct observation. An important application is when changes can be artifically induced in the object and when the changed specimen can be compared with itself before it was changed. Furthermore, holography offers color translation in amplitude and phase. Usually the phase information in conventional color translation techniques is completely lost.

The presence of amplitude and phase in the image means that the image bundle has been recorded in three dimensions. Therefore another important application is that a three dimensional sample of substantial volume can be stored on a two dimensional plate or film.

Since the hologram contains all the information about the object, the various image processing techniques that are normally applied to the original object can now be applied to the holographic reconstruction. This is a property that no other optical technique offers. Furthermore, this can provide an advantage over direct viewing of the object by various techniques, because in microscopy it is not always a simple matter to find precisely the same field of view when the specimen is moved from one type of microscope to another.



(a) no shear, unactivated IC (b) no shear, activated IC



(c) large tilt , unactivated IC (d) large tilt , activated IC

Figure 6. Differential Interferometry

Results of Various Techniques in Holographic Microscopy

Brightfield illumination is the simplest method of microscopy and image reconstruction. It is the unaltered reconstruction from a uniformly illuminated object. The major concern in this type of imagery is the limit of resolution. Figure 7 shows two reconstructions from the same hologram. The fibers and heads are neurons. The arrow indicates a nerve which has a lateral extent of 1 µm. The reconstructions were taken in two different planes of the specimen about 40 µm apart in depth. The wavelength of the light was 6328Å. An oil immersion microscope objective was used with a 50x magnification and a N.A. of 0.95.

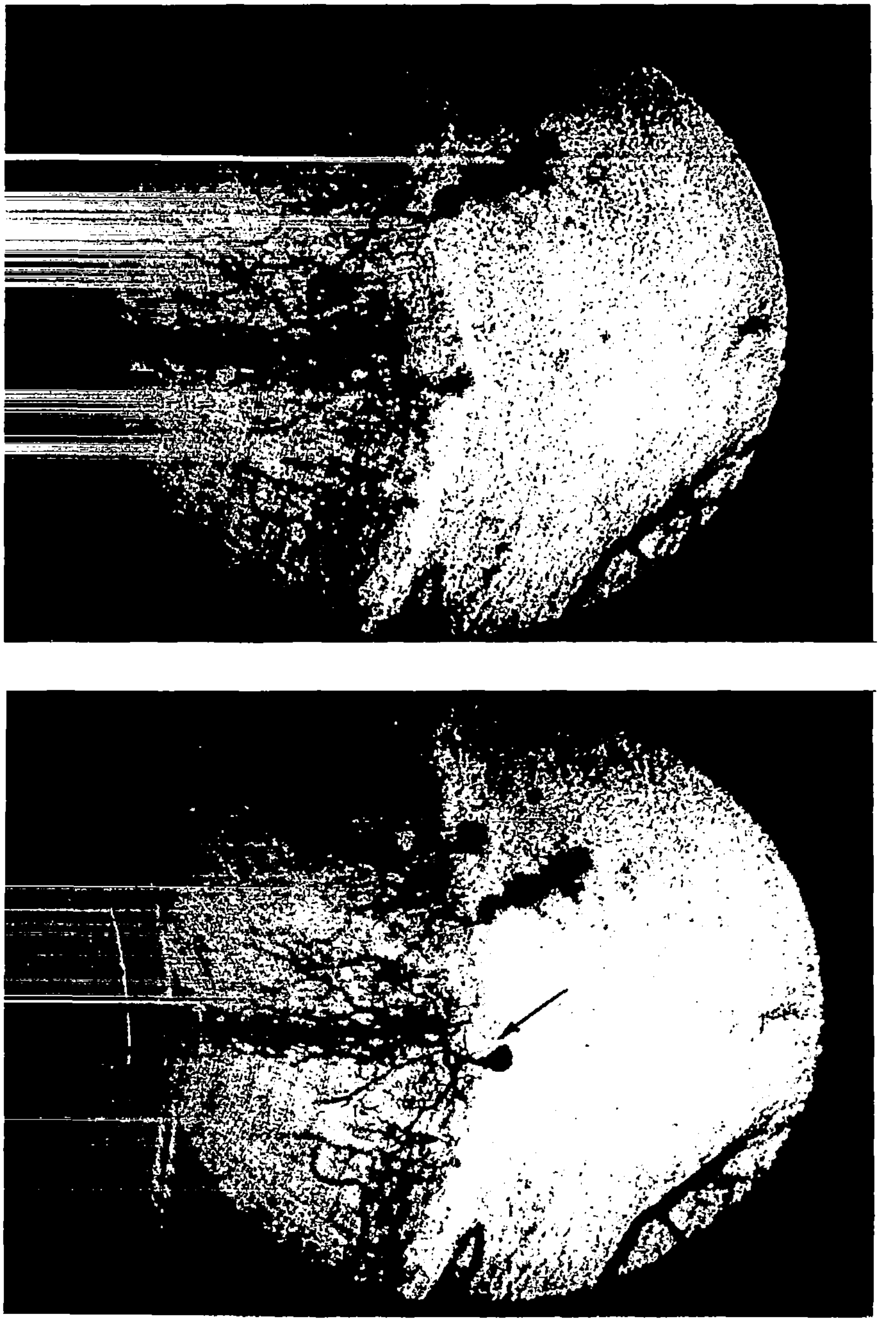
The arrangement of the Holographic Microscope is given in Figure 8. Two other brightfield reconstructions are shown in Figure 9; the hologram was taken with a 20x, N.A. 0.50 dry objective.

Darkfield results can be obtained by suppressing the zero-order diffraction image of the object illumination source in the reconstruction. This was shown first by G. Ellis,[2] but unfortunately his image quality was poor. However, as shown by Figures 7 and 9, techniques do exists for substantially improving the image quality.

Vertical illumination has not been shown in the literature, but does not offer any serious difficulties.

Stereo viewing is a technique that has not been applied in holographic microscopy.

Figure 10 shows reconstruction of a phase object from one hologram made from polybutene oxide. Photographs (b) and (c) show results of Schlieren knife edge techniques applied in the reconstruction. This is an example of a method where phase variations are made visible. More precisely it falls in the category of edge enhancement techniques. Frequently these techniques are used in windtunnels and in testing of large optical systems. The phase gradients appear more pronounced. The insertion of the knife edge, however, cuts the useful aperture in half in one direction, causing a drop in resolution in that direction. It does not mean that the fidelity of the image is not correct. A better method is oblique brightfield but here the contrast produced in the image is not as good. However, because the angle used in oblique illumination is different from zero the diffraction image is linearly displaced.



a

b

Figure 7. Neurons; (a) Reconstruction from a hologram of a microscopic specimen. (b) Reconstruction from the same hologram 40 μm deeper. Arrow indicates a fiber of about 1 μm mag. around 100×.

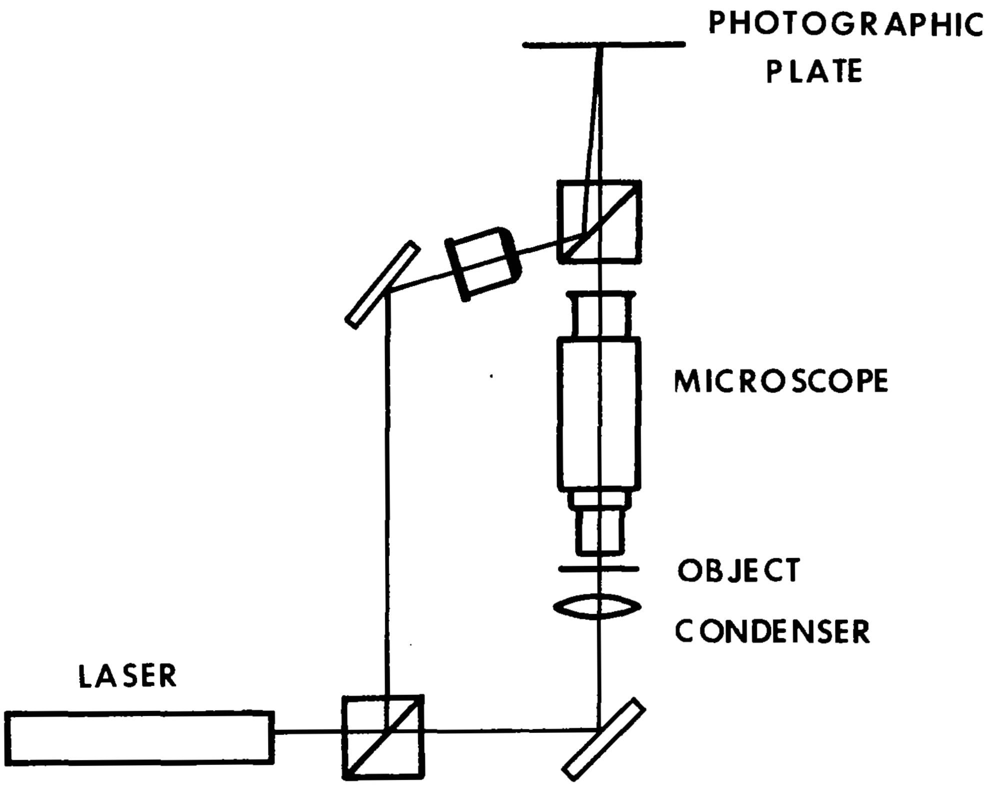


Figure 8. Schematic diagram of the Holographic Microscope.

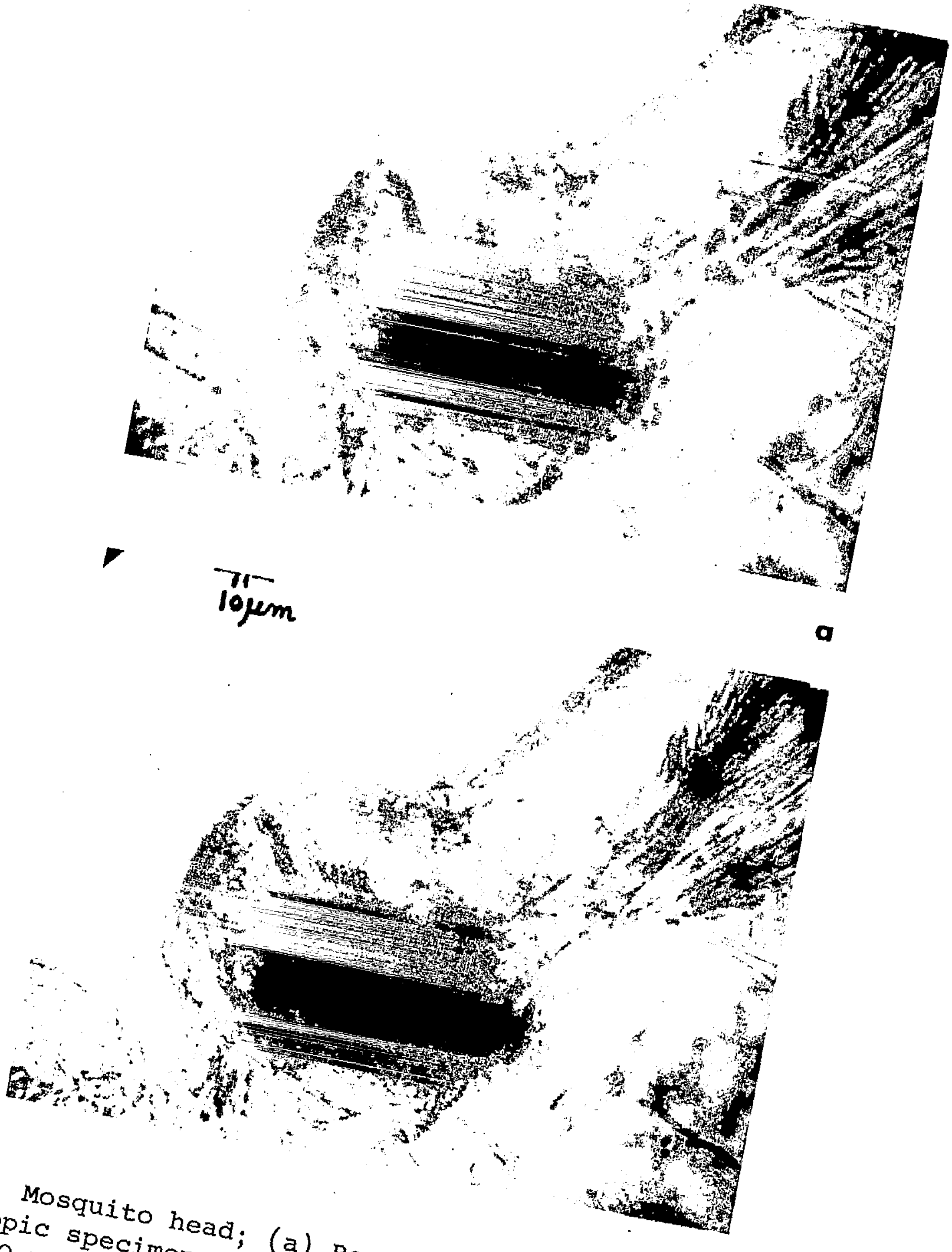
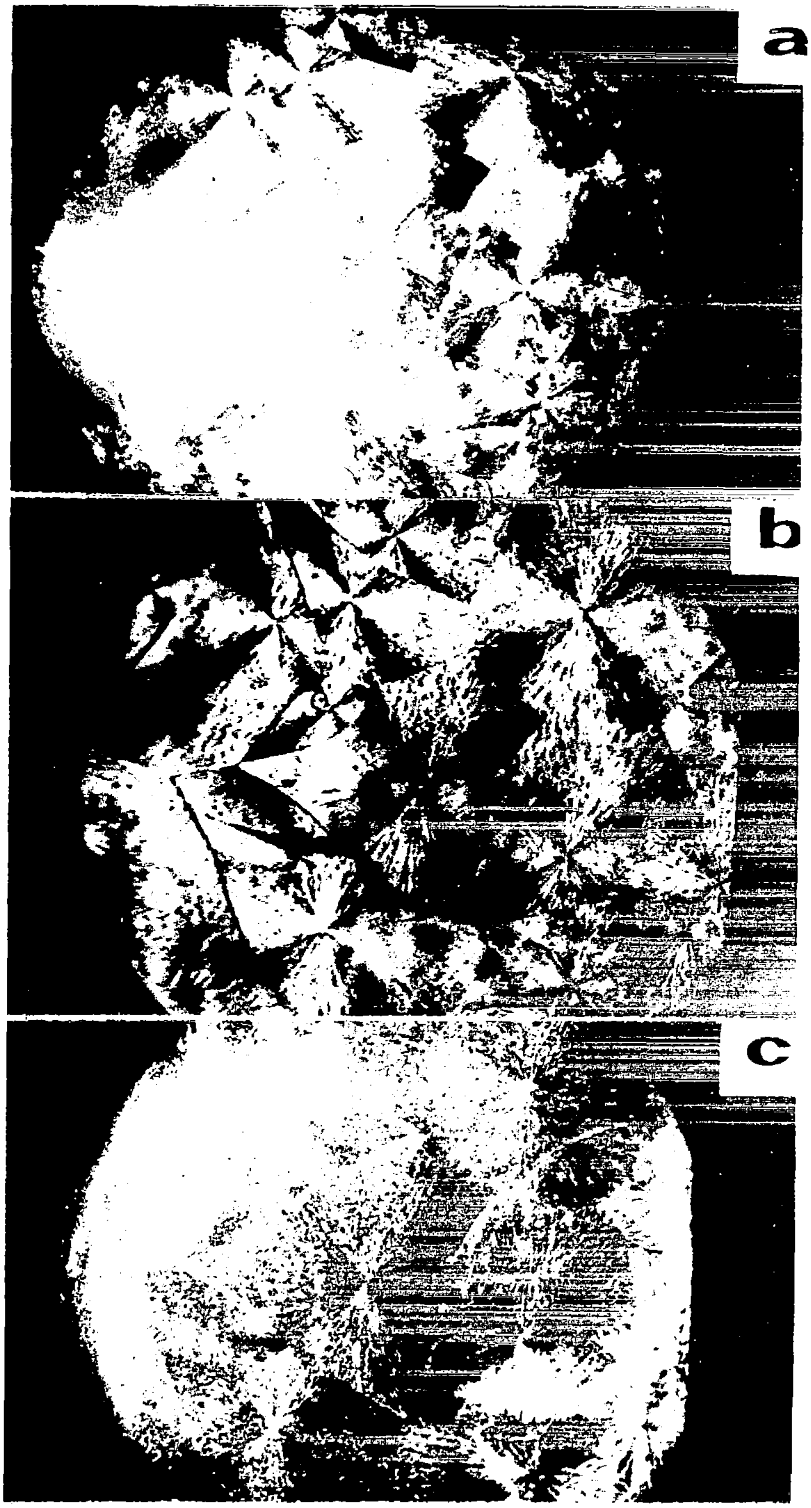


Figure 9. Mosquito head; (a) Reconstruction from a hologram of a microscopic specimen. (b) Reconstruction from the same hologram but now 150 μm away in depth in the specimen. Mag. around 200x.



Straight brightfield reconstruction.

Toepler Schlieren.[8] The knife edge is inserted into the diffraction image masking half of the diffraction image but just allowing the undiffracted zero-order to pass.

Same as (b) but now the knife edge also masks the zero-order diffracted component. The image thus obtained is akin to oblique darkfield illumination.[8]

Figure 10. Polybutene oxide; Schlieren or knife edge techniques; reconstructions from same hologram. Mag. 200×.

Two beam normal interferometry during reconstruction is adequately shown in Figure 11. The hologram was taken from a sample of polyethylene oxide on a hot-stage. In (a) in the solid part it can be seen that the polymer develops in platelets stacked like a deck of cards, but the orientation of the deck differs from place to place. In the molten part there is no order. In (b) inferences about the phase difference can be made from the form of the interference fringes. This work was done in collaboration with Professor Marian Rhodes of the Polymer Institute at the University of Massachusetts. The event seen in the reconstruction only lasts for about 1 second. The exposure time on the hologram was 1/1000 second on Agfa Agepan FF film (now 14 C 70). The laser used was an AO He-Ne laser with an output of 4 mW.

Figures 12 and 13 show examples of small shear interference contrast. In Figure 12(a) the blood cells show some contrast which normally, in red light, cannot be seen. The reason is that Brownian motion takes place and a phenomenon like time integrated interferometry occurs.[12]

It is apparent from Figure 12(b) that the phase information is still present in spite of the Brownian motion. Although this small shear interference contrast can be considered an edge enhancement technique, it is actually more than that. The contrast is so good that a high degree of resolution is obtained with the full aperture of the microscope objective. The fidelity of the image does not suffer. The human perception system immediately recognizes the shape and views the pictures as if they were taken from objects that were illuminated obliquely with a highly directed light bundle.

Figure 14 is introduced to make a comparison with the results in Figure 10(b). The fibrils are much sharper in Figure 14(b), illustrating the advantage of not occluding half the aperture as in Figure 10(b). The same fibrils are detectable, but in Figure 10(b) they appear more smeared out.

Phase contrast was shown by Ellis.[2] The image quality is not good in his case, but as has been described earlier, techniques exist for substantially improving the quality of the image.

Polarization microscopy was adequately shown in Figure 10(b) and 14(a). The dark crosses are caused by the birefringence in the polymer. The hologram was made with a laser emitting plane

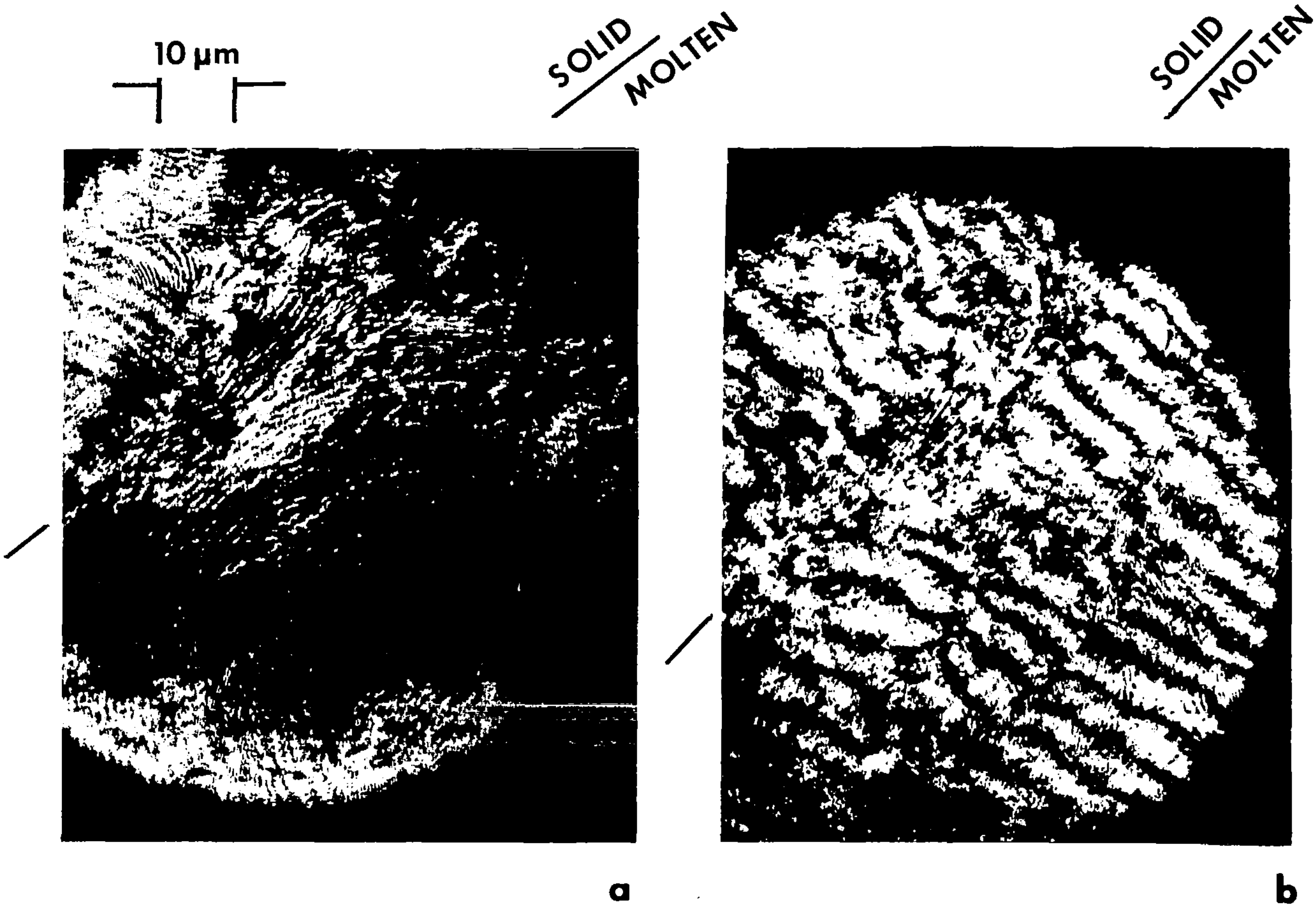


Figure 11. Front between molten state and solid state of polyethylene oxide. Reconstructions from the same hologram. (a) small shear interference contrast. (b) normal two beam interferometry. Mag. 1000×.

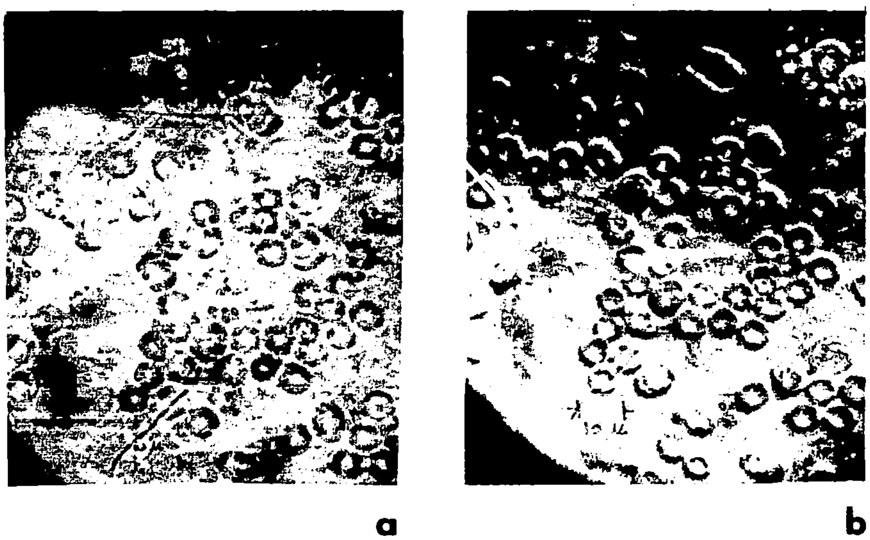


Figure 12. Human fresh red blood cells; reconstructions from same hologram. (a) straight brightfield reconstruction. (b) small shear interference contrast. Mag. 750×.

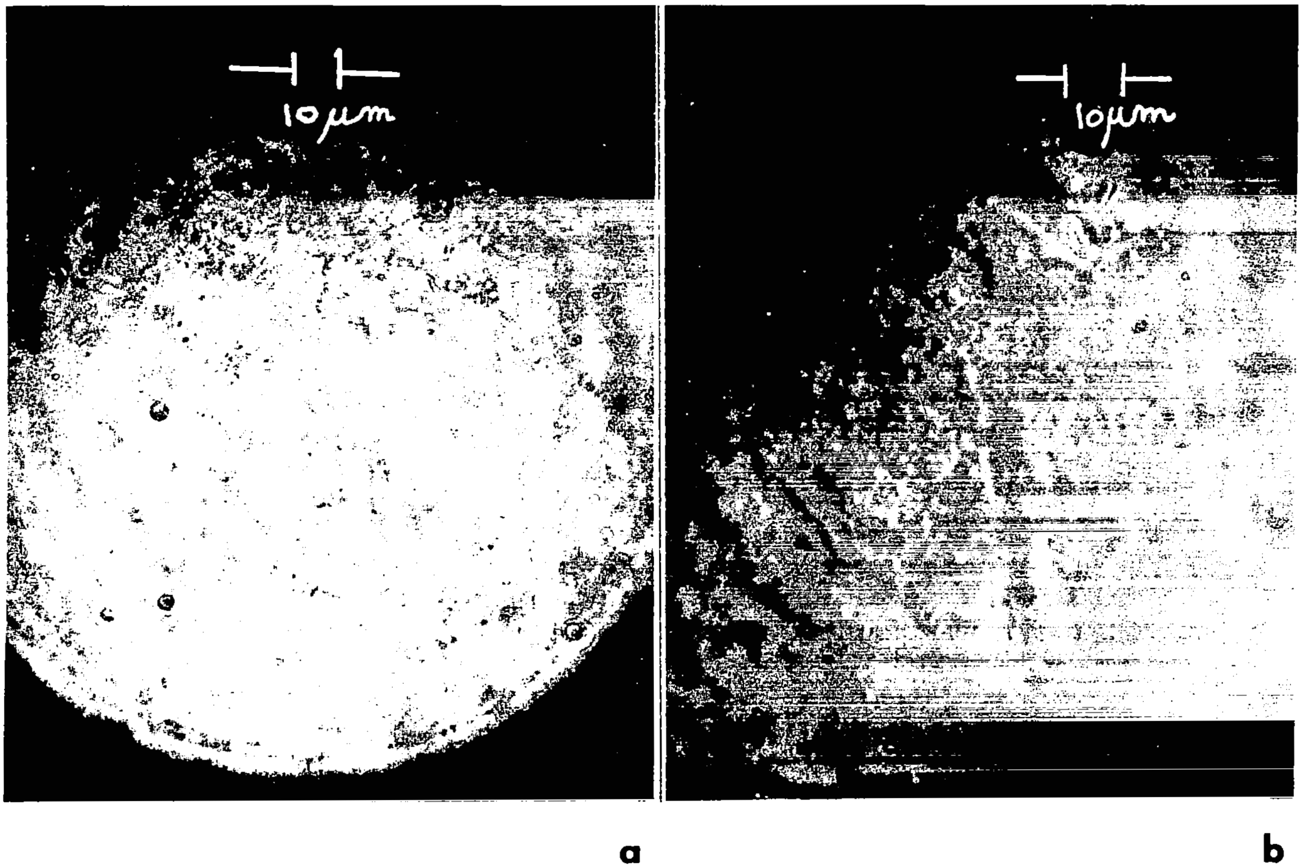
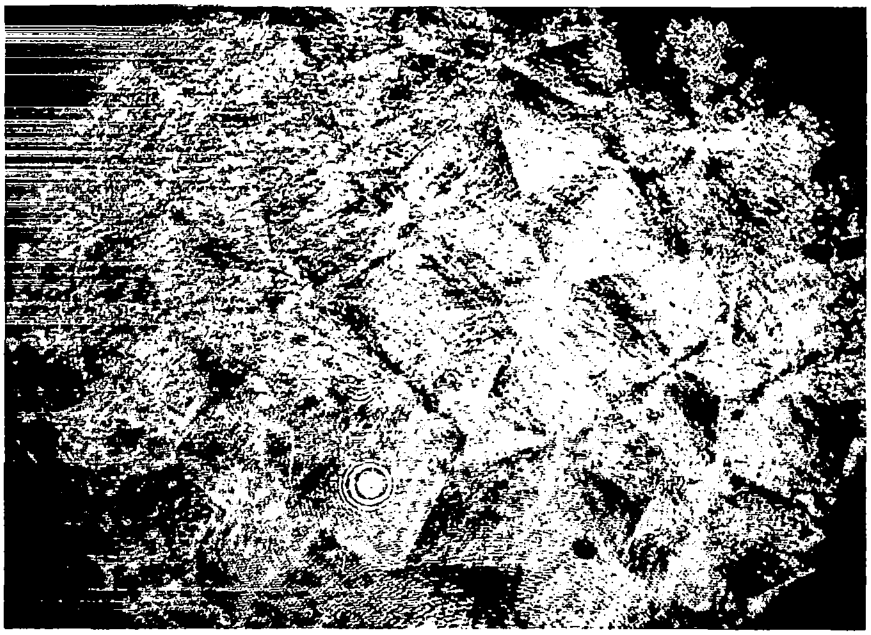


Figure 13. Epithelial cell, reconstructions from same hologram. (a) straight brightfield reconstruction. (b) small shear interference contrast. Mag. 750x.



a

b

Figure 14. Polybutene oxide; reconstructions from same hologram. (a) straight brightfield. (b) small shear interference contrast.

polarized light. Under ordinary conditions, the interference at the hologram plane takes place between mutually parallel polarized light in the two beams. This means that the hologram contains information of the specimen as if were taken between a polarizer and analyzer both being set parallel. Introduction of a rotator in the reference beam[3] or object beam, will allow a reconstruction of the specimen representing information between polarizer and analyzer with an arbitrary angle with each other. This work needs to be done during the production of the hologram and poses no difficulties in the reconstruction.

Time Sequential Holography

A result that currently can only be achieved with holography is the comparison of an object with itself after an event has taken place. The information thereby obtained is in amplitude and phase. This permits the comparison to be done with interference and phase techniques as well as amplitude techniques, such as is done with comparators. Powell and Stetson[13] showed an integration of the sequential events. This is necessary in cases where the time interval between the events is short. An example of this is also given in Figure 12(a). Heflinger, Wuerker and Brooks[13] showed time sequential holographic interferometry by making a hologram of a light bulb, and then repositioning the hologram in the same plane where it was taken to interfere the reconstructed image with the lamp itself. When the lamp is heated an interference pattern appears which is characteristic of the change in optical path due to temperature elevation. This method can be applied to the visualization of strains, growth of crystals, changes in biological specimens etc. Instead of superposing many holograms on the same emulsion for different conditions of the object, a finite number of different holograms can be made of different photographic plates. If the plates are then stacked together, an interference pattern results similar to superposing all the holograms on one plate. The information derived from these techniques is mainly phase-information.

Figure 14 is introduced to make a comparison with the results in Figure 10(b). The fibrils are much sharper in Figure 14(b), illustrating the advantage of not occluding half the aperture as in Figure 10(b). The same fibrils are detectable, but in Figure 10(b) they appear more smeared out.

Phase contrast was shown by Ellis.[2] The image quality is not good in his case, but as has been described earlier, techniques exist for substantially improving the quality of the image.

Polarization microscopy was adequately shown in Figures 10(b) and 14(a). The dark crosses are caused by the birefringence in the polymer. The hologram was made with a laser emitting plane polarized light. Under ordinary conditions, the interference at the hologram plane takes place between mutually parallel polarized light in the two beams. This means that the hologram contains information of the specimen as if were taken between a polarizer and analyzer both being set parallel. Introduction of a rotator in the reference beam[3] or object beam, will allow a reconstruction of the specimen representing information between polarizer and analyzer with an arbitrary angle with each other. This work needs to be done during the production of the hologram and poses no difficulties in the reconstruction.

INSPECTION OF INTEGRATED CIRCUITS

From previous Sections it has become clear that information about an object can be stored and restored in amplitude and phase through use of Holographic Microscopy. From an applications point of view, Time Differential Holography will be in all probability the most important.

As shown in the last Section, Holographic Microscopy is capable of very high resolution. It should also be remembered that a sensitivity of $\lambda/100$ OPD in reflection can be achieved in two beam interferometry with little difficulty. Together, these characteristics can be put to use in the inspection of integrated circuits. In the following, a treatment will be given of the different applications of Holographic Microscopy to this inspection. One of these investigations was carried out under this contract. Table II summarizes the use of the various types of Holographic Microscopy for the different steps involved in making integrated circuits.

For active inspection it is assumed that some quantitative probe is made about a pertinent property of the IC. Therefore it is appropriate to consider the possible use of interferometry; in particular normal interferometry and differential interferometry.

Table II Some Relations between Inspecting IC's and Holographic Microscopy

Integrated Circuit Inspection	HOLOGRAPHIC MICROSCOPY			
	High Resolution Interferometry	High Resolution Data Storage Large Depth	High Resolution Differential Interferometry	High Resolution Large Field Large Depth Data Storage
Etching	X	X	X	
Oxidation	X	X	X	
Metalization	X	X	X	
Diffusion	X IR	X IR		
Bonds at chip pads	X	X	X	
Temperature Distribution	X	X	X	
Printing				X

Recalling that normal interferometry is the comparison between a uniphase wavefront and another wavefront, measurement is made of the departure of the other wavefront from the uniphase wavefront. Starting with the silicon wafer during the different processes of etching, metalization, diffusion and oxidation, it may be important to measure the etching depth from the wafer surface. If the total surface has to be examined, the wafers must be well polished and flat to permit interferometric inspection of the detail on the substrate by normal interferometry. The flatness of the substrate must be equal to that of the uniphase reference wavefront. This is of course too cumbersome and costly. If, however, the attention is concentrated on the area of the wafer of only one chip at a time, the flatness of that area is usually sufficient and comparing one chip with it's neighbor will not yield any appreciable difference in contour.

After the first step in the process of making the IC, the contour of the area within the confines of one chip is, in general, not a flat anymore. As more steps are executed, the contour changes more and more. Adhering to normal interferometry, it becomes increasingly difficult to measure, for instance, the OPD due to the etching depth of certain details within the chip because the departures from the uniphase wavefront begin to be too large. It is necessary, before a designed alteration is made in the contour of the chip, that the existing profile of the chip at that instant be memorized and used as the reference for the new contour to be created by the next processing. The philosophy of the memory of the last contour used as a reference leads naturally to Holographic Differential Interferometry. The reference is provided by the reconstruction from a hologram on which the contour is recorded of the previously executed process. The current contour is obtained from the actual chip. Interference of the two wavefronts yields interference fringes whose outlines represent an accurate measure for the change imposed by the process step just completed. This technique can be regarded as a deflection method.

The full sensitivity of Holographic Differential Interferometry is employed when a null-method is practiced during such an interferometric measurement. To achieve this the surface contour of each step of the process must be known. This being the case, holograms must be prepared which will give a reconstructed image bearing the known phase variations. This can be realized by carefully performing all the processing steps until a correct contour is achieved which will function as the object in making the reference hologram. For every step such a hologram can be made. Now the inspection is simplified by using, for every step, a hologram which bears the required phase map as a reconstructed image. The chip reflects a wavefront which is interfered with that of the reconstructed image. When the interference lines are perfectly straight the chip has assumed the correct contour. Any departure from straightness signifies a variation from the standard test unit. An example of this was shown in Figure 6(c) and (d). The first one shows the interference between two equal wavefronts; one derived from the hologram of the chip, the other from the chip itself. Mainly, unperturbed rather straight interference fringes are visible.

The second image shows the interference obtained in the same manner; only now, the chip was activated. If the expansion in the detail represented an error in a processing step, the deviations in the interference lines could be quickly measured and a determination of whether the unit was within tolerance could be made.

Figure 3 shows a drawing of the Holographic Microscope adapted to facilitate an IC on the stage. Figure 15 is a view of the actual Holographic Microscope. A fiber bundle is used to guide the light to the integrated circuit. The fibers are a special kind; the core refractive index, the cladding refractive index and the core diameter are so chosen that the fiber behaves like a waveguide[15]. The light is transmitted from one end to the other in a very organized fashion which generally is referred to as distinct modes. The fundamental mode makes the light issure from the fiber as one spherical wavefront, with a prescribed radiation profile.

When the phase of the light incident on the fiber is changed, the exit phase will change by the same amount. Because the fiber retains the same optical path independent of the bending, the exit phase will be independent of the degree of bending the fiber.

The center of the cone of light incident on the fiber determines whether the light issues in the fundamental mode or in one of the higher order modes. Once the entrance arrangement is adjusted and fixed for the fundamental mode, the other end can be freely manipulated rataining the same phase relation to the entrance end. Thus there exists a well prescribed phase relation between

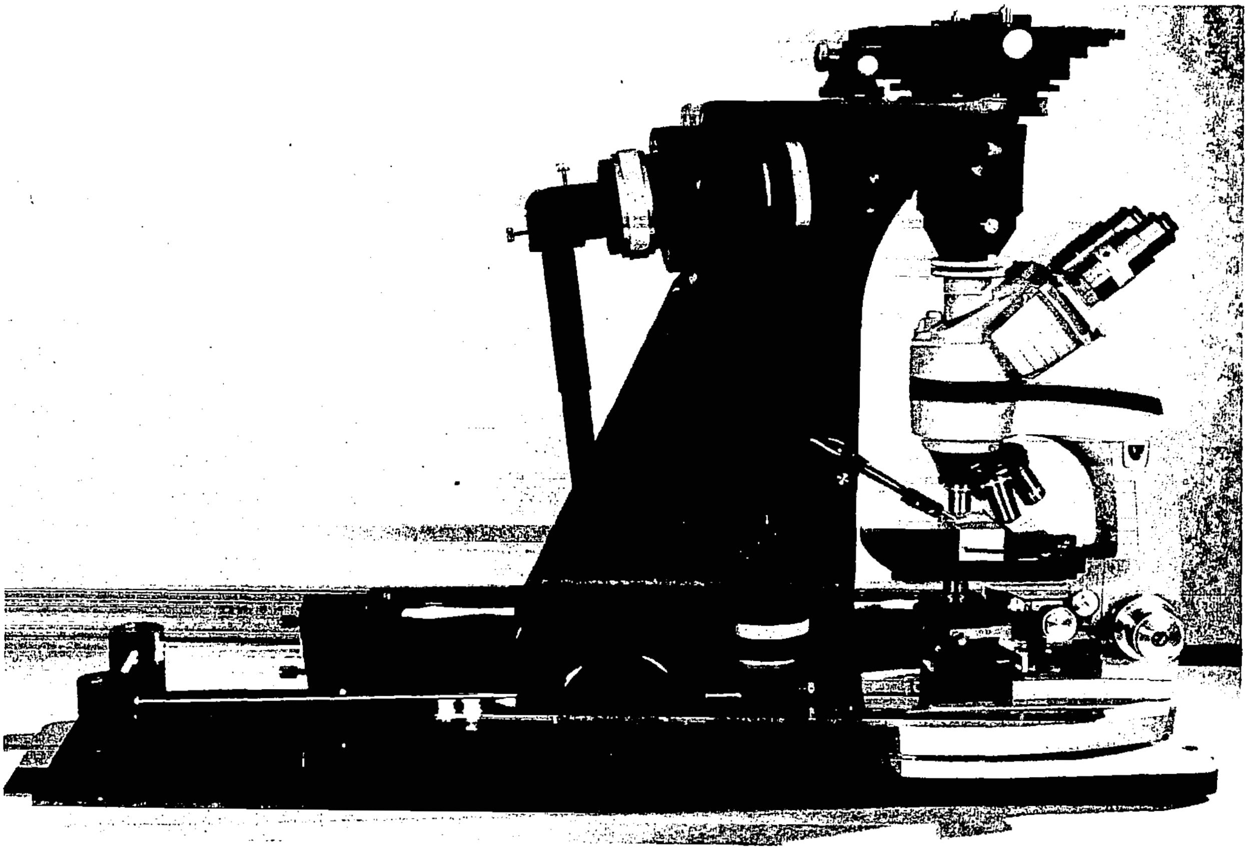


Figure 15. View of the AO Holographic Microscope. Note the stage on the top, which was specially designed under this contract to permit adjustments in the practice of holographic interferometry.

the reference beam and the beam coming from the fiber. It means that when initially coherence existed between the object beam and the reference beam, there will still be coherence between the object-beam and reference beam when a single-mode fiber is employed in either light bundle. The fiber has the added advantage that any imperfections in the optics before the entrance of the fiber that cause a disturbance in the wavefront will be totally eliminated. The wavefront incident on the object is thus always clean.

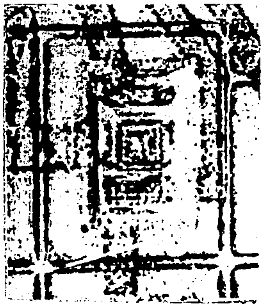
On top of the Holographic Microscope, as shown in Figure 15 is a 4-way stage, 3 linear motions and one rotational around the vertical axis. This stage accepts a film plate holder used to make the hologram. After development of the plate it can, with the aid of an adapter, be repositioned on the 4-way stage and adjusted to choose the fringe patterns as shown in Figure 6. This part of the instrument was specially designed under this contract for use of the microscope with integrated circuits. In this form the instrument can be used to measure quantities mentioned in the earlier portions of this Section. It is also capable of accepting IC's to do the experiments as illustrated in Figures 4 and 6; i.e., measurements on the IC after it has been stemmed. The property to be measured is the thermal distribution over the face of the IC. Actually it is not possible to deduce a temperature map over the integrated circuit but an accurate relief map of expansion induced by the heat capacity distribution in the IC as well as the temperature is produced. In areas where impurities resist a current, the expansion may locally be larger and show in the interference pattern.

In Figure 16 such an expansion is shown to occur between the unactivated and activated state. In the righthand column it is obvious that a change has occurred when compared with the left hand column. In the top row the detail shown in the center goes from a rather flat appearance to a more swollen one. Some shadowing around the detail shows this swelling. From the bottom row an estimate of the extent of the expansion can be derived. The arrows drawn in Figure 16 focus the attention on that one particular area where the estimate was made of the swelling. In Figure 16(c) the straight dark band indicates that in that region the phase takes a given value. The relative straightness of the edge of the band means uniformity of the phase. It should be remembered that the interference pattern comes about by comparing the actual IC-wavefront, with an IC-wavefront derived from a hologram. The relative straightness thus indicates that the actual IC contour did not change compared to the situation when the hologram was taken. After the IC was activated however, the situation in Figure 16(d) is effective and in the same area the straight dark fringe has changed into an irregular fringe. Going from right to left in Figure 16(d) in the indicated area, first a white band shows, then follows a dark area and then a narrow white band which winds around irregularly. The phase difference between the darkest and the adjacent whitest area is a half wavelength ($\lambda/2$). The swelling at the end of the arrow has occurred over a height of $\lambda/2$. When a different wavelength is used for the reconstruction and interference process than during the process of making the reference hologram, some account should be taken of this fact. When the same wavelength is used for both steps, the expansion is $\lambda/2$ at the indicated point. Thusfar the images were obtained by reflecting light off the surface of an IC. Consequently no information is obtained from the medium under this surface.

To alleviate this problem it is possible to make use of the fact that silicon has a window in the infrared around the wavelength of 1μm. This permits the radiation to penetrate into the diffusion zones and whatever part of that radiation is captured, it carries information about the semiconducting junction. Interferometry in the infrared in general offers a method to carry that information in an implicit form. The complexity of the detail on the integrated circuit and the lack of optical preparation of the circuit makes it imperative that holographic interferometry be used. The same techniques and methods can be used as were described for the visible spectrum. During the prototype stage sequential Differential Holographic Interferometry can be applied. It is necessary to use an image converter to observe the interference pattern.

Figure 17 shows a print of a hologram made in the infrared. Figure 18 is a reconstruction made from the hologram shown in Figure 17. This image can be compared with the images made by conventional photography in the IR as shown in Figure 19. The film emulsion used to make these holograms was Eastman Kodak I-Z. The graininess of this plate is very high and becomes apparent in the reconstruction.

Finally Figure 20 is an example of Infrared Holographic Interferometry made from the wafer. This is a comparison of the object wavefront with the reference reconstructed wavefront.



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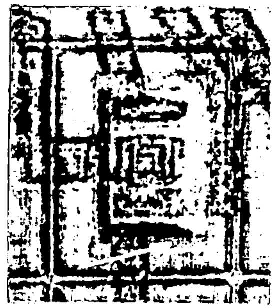

b

c

d

Figure 16. Enlarged version of Fig. 6. The areas marked in Fig. 6 are shown here in the same order.
(a) small shear unactivated (b) small shear activated
(c) large tilt unactivated (d) large tilt activated

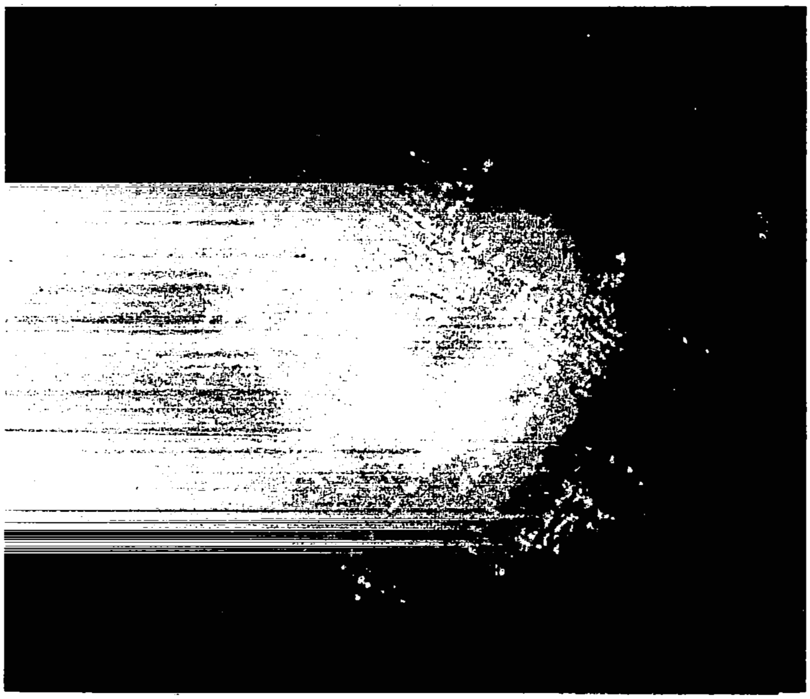

Figure 17. Hologram made in the infrared.

Figure 18. Reconstruction from hologram made in the infrared.

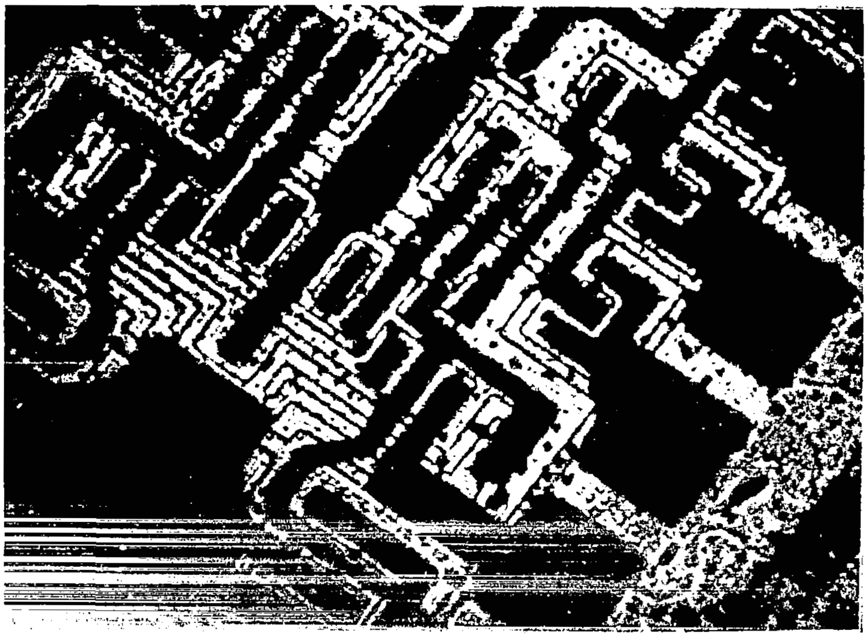

Figure 19. Direct images made from IC with infrared source.

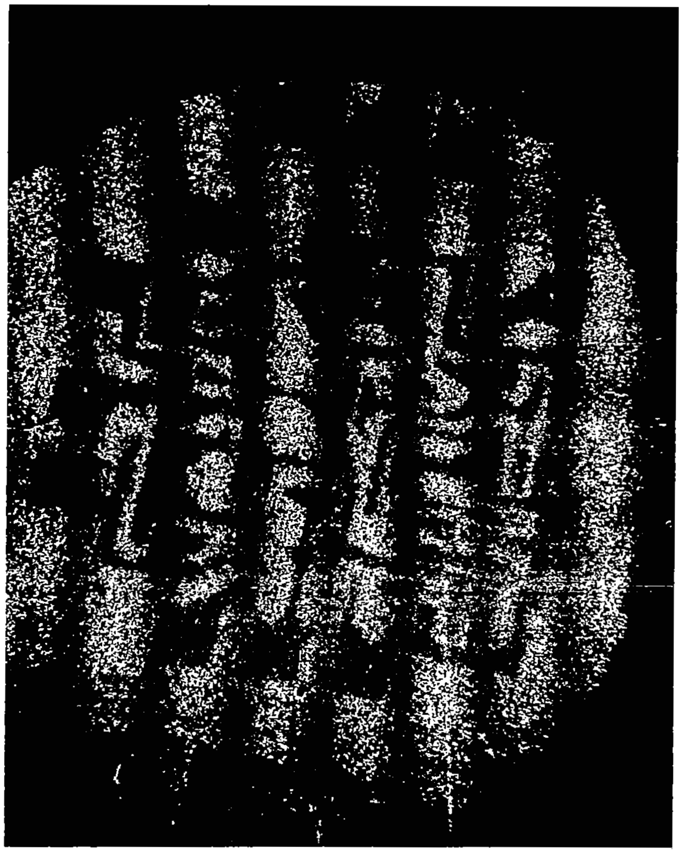

Figure 20. Holographic interferometry in the infrared.

There was no change between the two situations and as a consequence the fringes are straight.

All the infrared holograms were made by letting the object bundle transmit through the wafer. As can be seen in Fig. 20, for instance, the aluminum masks out areas under which semiconducting junctions may be present. Before stemming the IC it would be more useful if the object beam were incident on the back of the IC and reflected from the aluminum. The information from these holograms together with that of the transmission holograms produce a complete picture of the optical behavior of the medium.

Experiments to perform IR-holography in reflection from the back of the IC yielded very poor results. There appeared a strong noisy pattern in the reconstruction, which is attributable to the rough surface finish of the back side of the wafer. Unless immersion oils for 1.15µm can be found to match the refractive index of the silicon or unless new illumination techniques can be found, or unless the back surface is polished the back-illumination IR-reflection technique is not to be considered feasible.

RECOMMENDATIONS

Before making recommendations it is appropriate to recapitulate the lessons learned from this study. The retention of phase in the holographic process has been extensively studied for application to detecting failures in integrated circuits. Although no actually failing components were used for the study the usefulness to detect local abnormal expansions was established. This can be seen in Figure 6a, b, c and d as well as in Figure 16a, b, c and d.

The second fact of significance is that these interference techniques can also be made in the invisible spectrum; in particular, where the materials of the IC beam properties that will be manifested by irradiation with such wavelengths; e.g., interaction of light and electron migration. The use of infrared light to make the hologram and perform interferometry is shown in Figure 20. The wavelength used was 1.15µm of the He-Ne laser. The silicon wafer is transparent to this wavelength and phase-changes occurring in the semiconducting layers can be made observable when this wavelength is used.

These two properties, the use of holograms to make a reference wavefront of prescribed contour and the use of wavelengths of significance to the materials of the IC, offer several applications.

During the prototype stage it is possible to follow one and the same chip in its evolution to completion and with the aid of the electrical probes, correlate the electrical behavior with the optical behavior.

As shown in Table II and the preceding Section in the production stage it is possible to make reference holograms for each step in the manufacturing process, be it in checking the depth of etching, the oxidation or metallization. It should be borne in mind that the sensitivity to detect optical path difference chances in around $\lambda/100$. An impurity that results in a deformation of that order of magnitude is detectable.

It is recommended that the instrument be used to follow a chip through it's evolution to a completely working IC. On the way the holograms thus obtained need to be saved and used as a reference for the next chip, or synthetic holograms should be used as references for the different steps of the IC fabrication. This experiment will reveal whether the hologram-reference system will offer advantages over the current techniques of an empirical nature.

It is recommended that the holograms be used to act as a reference, for later use. The storage of the optical path differences, have relevance to the irregularities in the IC and can be used for later assessment.

The principle can be considered as the equivalent of using the hologram as a test-plate used in optical fabrication. When a certain contour is required on an optical element, the usual procedure is to make a test surface of that contour put in opposite sign. As the polishing of the surface on the optical element proceeds, intermittent comparisons are made by holding the test plate against the surface under test. Interference fringes are focused due to the light trapped between the two surfaces. When the surface under test has taken the contour of the test plate, the fringes are straight. This type of testing has thus far been restricted to spherical and flat surfaces, because there have been no tests available to make the initial test plate.

Holography, however, offers the possibility of computer generating a hologram which, upon proper illumination, will yield a wavefront which has a prescribed contour. This contour can be so designed to yield a match with a contour of wavefront reflected off a surface under test. When those two wavefronts are interfered, straight interference lines will occur when they are equal in contour.

It is this concept that could be of great value to the prototype stage of the introduction of integrated circuits. Synthetic holograms can be made which within the complicated pattern could show a phase jump of any desired value. Such a phase jump on the IC could be a desired etching depth or an optical path difference created by a thin layer. When the interference between the hologram wavefront and the IC wavefront yields a pattern of straight lines, a perfect match is achieved.

In summary the concept of a Hologram Test Plate for contour measurements on integrated circuits should be studied. It is mainly a study of bringing into practice the known computer and optical techniques to produce synthetic holograms of high quality to function as the Hologram Test Plate.

It is recommended that an objective be designed to capture a large field of viewing angles. It will permit inspection from different aspects. Concurrent with this it is important to develop a technique to observe the reconstructed image from different viewing angles.

CONCLUSIONS

In conclusion the following program is proposed:

1. Build a microscope to suitably accept wafers and perform holographic interferometry on the wafers.

2. Conduct an experimental study to make a Hologram Test Plate (HTP) in conjunction with the holographic microscope. These HTP's carry exact wavefronts that match the desired contour of the IC at a given stage of production (in the prototype stage especially). It consists of computing the hologram on a digital computer and transferring it to an actual photographic hologram by optical demagnification methods.

3. Build a complete reconstruction arrangement to view and process images of integrated circuits that were recorded on holograms, on a later instant.

4. Perform a feasibility study to investigate the possibility of binocularly viewing the image reconstructed from a hologram. This will enable three-dimensional inspection for failures in leads and gold aluminum bonds of the leads to the pads on the chips.

5. Study the use of scanning optical microscopy employing lasers to accurately focus the light on the area to be inspected and optionally perform interference and phase techniques or record the image on magnetic tape and perform these techniques later.

The points proposed are all non-destructive methods necessitating no mechanical contact with the integrated circuit.

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